artillery control of avalanches along mountain highways

Noel C. Gardner
Arthur Judson

USDA Forest Service
Research Paper RM-61
October 1970

Forest Service
U.S. Department of Agriculture

Rocky Mountain Forest and
Range Experiment Station

ABSTRACT

Presents planning and operational procedures, and discusses criteria for avalanche control and the evaluation of avalanche hazard based on field data. Outlines a method for determining when gunfire should commence. Gives basic information necessary for formulating operational forecasts for highway maintenance and avalanche control personnel based on: mountain weather forecasts, traffic density, and current snow conditions. Explains instrument needs in detail.
Key words: Avalanches, snow density, anemometers, meteorological instruments, roads.

About the cover:
Sighting an artillery piece on the starting zone of Alta's Superior avalanche, one of several avalanches which threaten the busy highway between Alta and Salt Lake City, Utah. Photo courtesy of E. R. LaChapelle.

USDA Forest Service
Research Paper RM-61

October 1970

Artillery Control of Avalanches along Mountain Highways

by

Noel C. Gardner

Avalanche Consultant

Pincher Creek, Alberta, Canada

and

Arthur Judson

Associate Meteorologist

Rocky Mountain Forest and Range Experiment Station[1]

Fort Collins, Colorado

[1]U. S. Department of Agriculture, Forest Service, with central headquarters maintained in cooperation with Colorado State University at Fort Collins.

CONTENTS

FOREWORD

While practical experience and intuition have been the mainstays of avalanche control operations in the past, the increasing avalanche hazard on mountain highways calls for more reliance on instruments and semiquantitative methods for determining avalanche hazard. Snow is a difficult material to work with because it is constantly changing, and the spatial variations in its physical and mechanical properties are great. Further, it is difficult and sometimes dangerous to make observations and take measurements on snow in avalanche starting zones where such data are most valuable. On the bright side, techniques for evaluating avalanche danger are improving, reliable field instruments are more available than before, and data on weather, snow, and avalanches are now being gathered at some 21 mountain sites in North America. Research personnel are optimistic that the availability of large quantities of good data will eventually lead to useful new evaluation techniques.

Information presented in this Paper will aid field personnel engaged in avalanche operations; the techniques described here were tested and successfully used on a mountain highway in Canada.

Artillery Control of Avalanches Along Mountain Highways

Noel C. Gardner and Arthur Judson

Increasing winter use of mountain highways threatened by avalanches has intensified the need for good avalanche control programs. Although complete protection from avalanches is not economically feasible, a well-planned avalanche defense system including both artillery and structural control provides maximum protection at reasonable cost. Schaerer (1962a, 1962b) explains this well in his publications on the Rogers Pass project in Western Canada. Recent publications by Frutiger (1964), Mellor (1968), and by Frutiger and Martinelli (1966) provide much additional information on structural control.

The purpose of this Paper is to present planning and operational procedures necessary for effective control of highway avalanches by means of artillery; it will show how weather, snow, and avalanche data can be used to determine the timing of gunfire. When control measures are properly timed and applied in a sequence determined by avalanche behavior during past storms, protection from avalanches is achieved with only brief interruptions in traffic flow.

Techniques presented are based on work conducted at the avalanche stations at Rogers Pass, Canada; Berthoud Pass, Colorado; Alta, Utah; and several other locations in the mountainous west. They were operationally tested during the 1962-65 winters at Rogers Pass on the Trans-Canada Highway. Recommended instruments (see appendix B) were field tested at 10 mountain sites in the western United States and at Rogers Pass, Canada. Procedures for establishing blind-firing data were provided by the former chief of avalanche control at the 1960 Winter Olympics.[2]

While the avalanche control problem at Rogers Pass is more complex than at other areas in North America, the concepts treated here can be applied along any transportation route where avalanche hazard is serious. For example, the techniques could be directly applied on Red Mountain Pass in Colorado and on the Granduc access road from Stuart to Tide Lake, British Columbia. With slight modifications, they could be applied at several other locations in the western United States.

[2] *Personal communication with Richard M. Stillman, Rocky Mt. Region, USDA Forest Serv., Denver, Colo.*

The objective of artillery control of avalanches above highways is to artificially release snow accumulations under controlled conditions while traffic is stopped in a safe location. Creating small avalanches that stop short of the road is ideal. This is sometimes possible when highways traverse the runout zone of avalanches; it is not possible when the road intersects avalanches at midtrack level, as they do at many locations in the central Rockies. At such areas, the objective is to artificially release avalanches that produce small amounts of snow on the highway, which can be quickly removed by maintenance equipment.

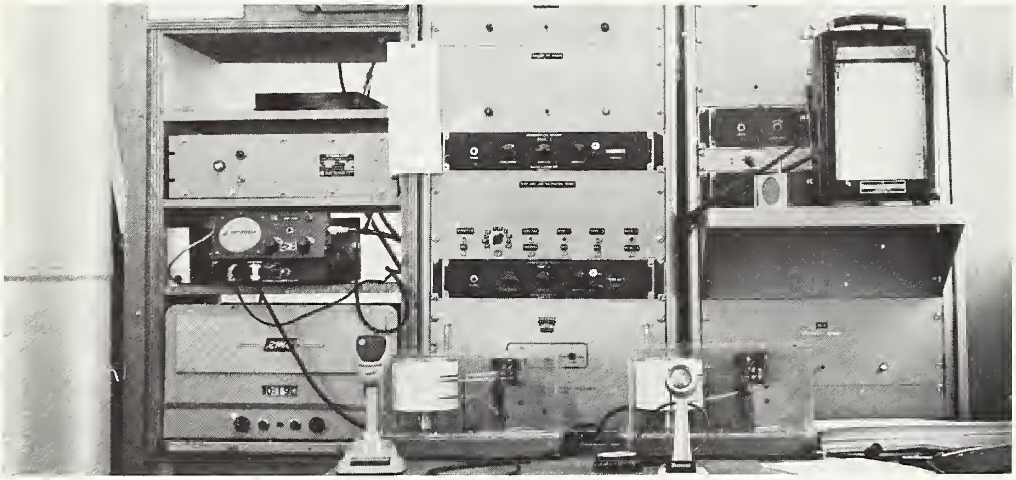
Avalanche hazard on highways can be minimized by an effective artillery program in all but the worst storm conditions. Control programs are considered effective when 95 percent or more of all avalanches affecting the highway are precipitated by gunfire.

Reduction of traffic stoppages due to natural avalanches is important, particularly along stretches where the slide density is high and multiple paths affect the road. For example, near Loveland Pass, Colorado, seven slide paths cross U. S. Highway 6 in one-half mile. The probability that one of these avalanches will strike a moving vehicle is much less than the strike probability for vehicles halted under these slides. For instance, if the fourth avalanche in the group ran across the road, traffic would be stopped on both sides of the obstruction, and cars would be directly exposed to the six remaining avalanches. Using the criterion that when one avalanche falls, others in the same vicinity are likely to follow, the hazard quickly becomes very high. This type of situation occurs frequently on highways where avalanches are uncontrolled, or where control measures are only initiated when traffic density is low and visibility is good. Such control in convenient, and would provide adequate protection if avalanches could be released with any degree of assurance after a certain amount of snow accumulated on the paths, but slides can only be released when snow is unstable.

Stability of both new and old snow layers continuously changes in response to variations in temperature and load; instability in snow is often short-lived. For this reason, continuous records on weather and snow conditions are basic to the suc-

Figure 1A.--Base station site at 6,500-foot level on Fidelity Mountain above Rogers Pass, British Columbia. Test field is located just beyond small building in left foreground. Eastern edge of test slope area appears in upper right-hand corner.

Figure 1B.--Main instrument panel inside base station. Multiple registers shown behind microphones on table record windspeed and direction from two remote mountain top sites. Temperature at 8,000-foot elevation near base station is recorded on the strip chart recorder upper right (binary readout). Microphones provide radio transmission to highway maintenance crews at valley location 3,000 feet below.



cess of the control program. When interpreted by an experienced avalanche hazard forecaster, these data make substantial monetary savings possible because of increased efficiency in control operations.

Criteria for avalanche control, avalanche hazard forecasting, and conduct of operations are discussed at length in this Paper. Fundamental considerations include a current mountain weather forecast, information on traffic density, and an evaluation of avalanche hazard based on field data.

I. PRELIMINARY CONSIDERATIONS

Locations for a base forecast station, remote sensing stations, and a level snow study plot must be selected with regard to access and safety. When a forecast area includes more than one climatic zone, additional stations are needed to give representative data on precipitation, temperature, and wind conditions in avalanche areas not represented by the base station instruments. An engineering survey is necessary to establish gun positions and locate targets. This permits gun crews to fire on targets as needed, regardless of visibility.

1. Location of Station and Study Areas

Base Station

The base station (fig. 1) serves as a data collection center where information on weather, snow, avalanches, and traffic density are received and analyzed. It should be centrally located within the avalanche area at an elevation and exposure representative of weather and snow conditions found at the midtrack level of many of the avalanches requiring control. The site should include a level test field 100 feet square suitable for the collection of basic snow and weather data. A small park surrounded by trees that provide shelter from wind is good, if the distance from the base station is not more than 5 minutes' travel on skis. The test field should not be within 200 feet of the nearest building, as snow deposition in such areas is influenced

by local vortices formed by windflow around buildings. Surrounding terrain should include a number of small avalanche-prone test slopes suitable for snow-stability checks during storms. The test slopes should be within one-fourth mile of the base station.

Base station access should be avalanche-free and open for oversnow vehicles even during severe storms. Wands spaced at intervals of 50 feet or less insure safe travel in "white-out" conditions.

Remote Stations

Remote stations are used to sample wind and temperature at starting zone elevations. A location at the head of a catchment basin in the center of the forecast area is desirable. Data can be transmitted to the base station by cable if the distance is less than 2 miles, or by radio telemetry for greater distances (Neal 1962). The number of remote stations needed is dictated by the amount of vertical relief, orientation and complexity of terrain, and size of the forecast area.

Selection of Representative Test Exposures

Avalanche-prone test slopes are selected in the vicinity of the base station. They should represent snow conditions in the starting zones of several avalanches in the forecast area. Exposure, elevation, loading characteristics, and relation to timbered areas are important considerations. Steep slopes (25 to 40 degrees) with several aspects are desirable. Slope distance from top to bottom should not exceed 300 feet for reasons of safety. Safe approach routes are needed. Final test areas should be chosen after the first one or two winters of field work.

2. Planning the Artillery Control Program

Targets

Target selection is time consuming, and requires experienced personnel and up-to-date contour maps; it is facilitated by a collection of good photographs that show the normal winter snow distribution patterns in the starting zones. Pictures showing fracture lines in these zones are especially useful. All significant catchment basins should be surveyed in winter, and again in summer after the snow melts. Select targets where high tensile stress concentrations are expected. Take advantage of convex slope transitions, steeply tilted snowfields beneath cornices, and the flaring of steep gullies.

In complex terrain where several starting zones lie at different elevations in an avalanche, locate the primary target on the highest release point, so the avalanching snow will trigger other starting zones as it descends. Care is needed in selecting high-elevation targets to insure that projectiles do not endanger areas beyond the intended impact point.

Two sets of winter photographs are needed. The first set, consisting of aerial obliques, must clearly depict starting zones, tracks, runout zones, and the highway. Selected targets are pinpointed on these photos. A second set of winter photos is taken from proposed gun positions. Targets on aerial obliques are transferred to the gun-position photos. This set is used for training and orientation of gun crews.

Gun Positions

Gun positions are chosen on the basis of crew safety, accessibility, and the number of targets that can be hit from a single location. Firing positions must be safe from avalanches and associated airblast in the worst storm and avalanche conditions. They should be accessible 24 hours a day, pre-

Figure 2.--Circular cement pad on east side of Rogers Pass marks gun site for 105 mm howitzer. Mt. MacDonald in background, rises 6,000 feet above Rogers Pass Highway.

cisely located, and must be easily identified. In the case of mobile weapons, wheel and trail positions are marked at a location along the side of the highway (fig. 2). Extra highway width, 60 feet in length, beyond the normal shoulder provides room for operating mobile guns. Gun positions that permit clear lines of fire to as many targets as possible are best. Firing over structures should be avoided; if it is absolutely necessary, the distance to the furthest structure must be less than two-thirds of the target range (Mellor 1968).

Suitable Weapons

Data obtained from the target and gun location surveys determine the number and type of artillery pieces needed for control. Fundamental considerations include accuracy, safety, range, and mobility. The 75 mm and 105 mm recoilless rifles work especially well where ranges do not exceed 7,000 yards. Both weapons require a two-man team, are highly mobile, and may be mounted in a pickup truck. When fixed mounts are desired, weapons are mounted on a cinderblock tower at a height above the maximum expected snow depth. This allows for backblast clearance, and provides storage space for ammunition inside the tower.

The 75 mm weighs only 167 pounds and is highly accurate up to 2,500 yards. The 700-pound 105-mm recoilless is more reliable at long range (to 7,000 yards), yet retains the accuracy and simplicity of the 75 mm. A shortcoming of this weapon is its limited traverse range (60° against 360° for the 75 mm). A shop modification will correct this inadequacy.[3] The 75 mm pack howitzer is also reliable, easily handled by two men, and is accurate to 9,000 yards. This weapon may be towed behind a pickup truck. Another highly mobile weapon is the commercially available avalauncher. With a range of 2,500 yards, this compressed gas gun can be fired in restricted areas due to its lack of backblast and shrapnel. It is a light weapon (about 200 pounds), costs approximately $600, and unlike most military weapons, is readily available for civilian use. A two-man crew is recommended. The avalauncher has a higher percentage of duds, is less accurate, and lacks the safety of military weapons. Research and development work now being conducted promise to alleviate these drawbacks in the future.

The 105 mm howitzer is recommended when the target range exceeds 9,000 yards. At 5,000 pounds, it is the heaviest weapon approved for avalanche control work. The gun requires at least a five-man crew; eight men are recommended for maximum efficiency. The projectile delivers sufficient shock to either stabilize or release snow in any starting zone. The weapon has a limited traverse range and its mobility is less than desired.

Two fuse settings are available with ammunition supplied for the military weapons discussed here. Fuses can be set with a screwdriver for superquick or 0.05-second delay. The adjustment slot is positioned on the side of the nose cone. Most ammunition is supplied with the superquick fuse setting already made.[3] This results in shell burst on the snow surface, which is desired in most control work. The delayed fuse setting is used when high-strength (hard slab) snow layers are underlain by fragile low-strength (depth hoar) layers deep in the snow cover. The normal procedure in such cases is to use a surface detonation round first, followed immediately by a round with a delayed fuse setting; a reverse order is preferred by some control teams. When the snow cover in a starting zone is exceptionally deep (10 m deep or more) a delayed round followed by a surface detonation is preferred.[3] Cornice control work also calls for use of delayed fuse settings, since an explosion at depth is most effective. Great care must be exercised in shooting cornices, as it is possible for delay-fused rounds to pass through the cornice and detonate as an air burst on the other side.[3]

Blind Firing Data

Blind firing data are recorded when the target area is snow covered so the powder marks can be clearly seen. The weapon is set in position, the target is bore sighted, an initial mil reading is obtained from the gunner's quadrant, and a test round is fired. The first round will fall below the target. The gun is then bore sighted on the powder mark left by the first round, and a new mil reading is taken. The difference between the two mil readings is added to the initial mil setting on the gunner's quadrant. The gun is then elevated to the new setting and a second round is fired. This projectile should be on target. If not, the procedure is repeated, and a third round is fired. A fourth round is seldom necessary. Aiming stakes are placed along the firing line to each target for horizontal control. Firing data for each target are

---

[3] *Personal communication with Richard M. Stillman, Rocky Mt. Region, USDA Forest Serv., Denver, Colo.*

recorded on waterproof cards, for later use by control teams.

Selection of Traffic Control Points

For safety purposes, all traffic must be blocked from the stretch of highway where artillery is being used. Vehicles are halted in a safe location called a ponding site. These sites should be:

1. Safe from natural avalanches and from sympathetic releases caused by shell bursts within the control area;
2. Large enough to hold all vehicles which will pass the control point in a space of 2 hours;
3. On a grade gentle enough to allow stopping without skidding into vehicles already stopped, and to permit starting without spinning out;
4. As free as possible from drifting snow;
5. Of sufficient width to allow cars and small trucks to turn around in the event of a prolonged delay.

Adequate barriers must be erected at traffic control points. These may be permanent gates that can be easily closed and locked, or portable barriers that can be carried in the back of a half-ton truck and quickly erected across the highway by one man. The barrier must be clearly identified with appropriate color and signing. Warning signs of approach to the roadblock are posted at the entry to the ponding area. Each traffic control area should be manned by a member of the highway department using a radio-equipped four-wheel-drive vehicle. The vehicle should be equipped for towing and winching, and should contain first-aid supplies and avalanche rescue equipment.

II. OBSERVATIONS AND INSTRUMENTATION

Detailed observations on weather, snow, and avalanches are essential to any evaluation of avalanche hazard. Continuity of the data are also important, because methods used to determine when control action should begin depend on continuous records.

3. Data and Instrumentation

Wind

Windspeed and direction should be continuously recorded from an exposed peak or ridge at an elevation and position representative of a large number of starting zones in the control area. Recorders should be located at the base station in a heated room. A rugged wind system that will withstand windspeeds up to 125 m.p.h. under icing conditions is needed. The standard 3-cup S-type (beaded, conical, copper cups) anemometers (fig. 3) are satisfactory and have been used at mountain weather stations throughout the western United States and Canada. Six-hour averages of windspeed and direction are adequate for assessing snow transport into catchment basins, although shorter intervals are used during certain storms.

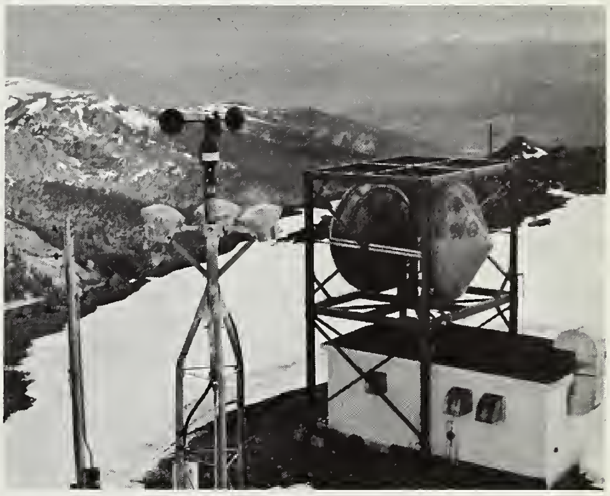


Figure 3.--Beaded, conical, copper cup, generating anemometer on a 3,810-m mountain summit near Berthoud Pass, Colorado. This is the Weather Bureau Model F-420 windspeed transmitter. The three 300-watt incandescent lamps prevent rime formation on the cups and provide a total radiant flux of 0.5 watt cm^{-2} to anemometer.

Basically, two types of wind systems can be used. One utilizes electrical contacts on both vane and anemometer, and requires from 6 to 12 volts D.C. The vane transmits eight directions and the anemometer each mile of wind travel. An operations event recorder, with a chart speed of 3 inches per hour, contact arc suppressor, and power supply are needed with this arrangement. The other wind system consists of a variable-resistance vane and an anemometer which is a D.C. generator. A twin-channel analog recorder with an internal resistance of 1400 ohms and a 1 milliamp full-scale pen deflection is used to record windspeed and direction. The generating anemometer does not require power, but the vane requires a 5 volt D.C. power supply.

The anemometer circuit utilizes a 5K ohm trim potentiometer in series with the recorder and a 2K ohm trim potentiometer in parallel with the recorder to make it possible to adjust for the resistance offered by long land lines. Both anemometer and vane circuits are fused to protect the recorder from line surges.

The U.S. Weather Bureau's model F-420 anemometer and vane have proven to be reliable in severe mountain weather, and are recommended for the analog wind system. A post-factory modification is needed on this anemometer.[4] The analog wind system gives more complete data than the contact system, although it requires greater technical know-how for calibration and maintenance. Six-hour averages are closely approximated by averaging the first 15 minutes of every other hour from the analog strip chart. Peak gusts are read directly from the chart. A chart speed of 1½ inches per hour is recommended for ease of reading without undue loss of detail.

If cable is used with either system, it should be shielded and either buried or supported on telephone poles at a height exceeding the maximum expected snow depth. A carrier cable is necessary for overhead cables. Icing, lightning, animals, snow creep, water, and bulldozers are common sources of trouble with cable systems.

Anemometers at exposed locations become covered with rime and require infrared heat units; 2.5 cm of soft rime on a cup anemometer reduces rotational velocity by 50 percent at 30 m.p.h. The minimum radiant flux needed to de-ice anemometers under most icing conditions is 0.5 watt per square centimeter. This is provided by 900 watts of radiated power from incandescent lamps (fig. 3) at a distance of 45 cm below the cups (Judson 1969). The cups should be painted a high-gloss black. When 110 volt power is not available and rime is a problem, it is necessary to search for a less exposed site near or below timberline. Relation of wind at this site to that at the more exposed location should be checked by running anemometers at both locations when there is no riming. Other things being equal, tower-mounted ridgecrest anemometers (fig. 4) give better data, are less influenced by local terrain, and are preferred over wind sensors at sheltered sites.

Figure 4.--Weather Bureau F420-C anemometer and vane on a 10 m series 25 Rhone television tower in the Colorado Rockies. Minimum size of pipe recommended for mounting mountain wind sensors is 1 5/8 inches, outside diameter. Anemometer is elevated to avoid air-flow interference from vane.

Temperature

Air temperature is required from the base station study field. Maximum, minimum, and current temperatures are read every 12 hours from standard liquid-in-glass thermometers mounted in a standard instrument shelter. Additional readings are needed when starting zone elevations are more than 1,000 feet higher than the base station. In this case, temperatures should be transmitted to the base station from remote stations along with wind data (fig. 5). Precalibrated thermistors housed in special radiation shields make good remote temperature sensors. Their output may be recorded on either analog or event recorders. When using the latter, the temperature is read out in binary. Use of remote sensors will determine the elevation of the freezing level during storms that produce rain in lower elevations. Determination of this level is a critical factor in avalanche hazard forecasting.

Precipitation Measurements

Precipitation is measured at the base station test field. Measurements should be representative of conditions at the midtrack level. A recording rain and snow gage with a 7-day clock and an electric chart drive, snowboards, and snow stakes are used. The recording gage provides a continuous record

---

[4]For details, contact ESSA Weather Bureau Reconditioning Center, Joliet, Ill.

Figure 5.--Wind and temperature sensors at a remote station in the Colorado Rockies. Generating anemometer on left, variable resistance vane center, contact anemometer right, and radiation shield housing thermistor for temperature readings.

of precipitation. The 8-inch can is used as the standard 24-hour precipitation amount for historical records when it is known that rain occurred, or when the water-equivalent core reading determined from the 24-hour snowboard is affected by local drifting.

Four snowboards give additional information needed at the base station. They are portable and have a plywood base with an area of about 1,000 cm^2. Attached to the base is a meter stick reinforced by wood or metal backing. Total snow depth on the ground is read from a permanently anchored snow stake. Height of this stake should exceed the expected maximum snow depth at the site by at least 1 m. All stakes and snowboards are painted white to reduce radiation melting. The four snowboards are clearly labeled to avoid confusion. The first of these is the **storm board**. It is set flush with the snow surface and remains in place until the end of each storm, when it is cleaned and reset flush with the new snow surface. This board gives cumulative new snow depth during storms. It gives valuable information on settlement when compared with other snowboards, if wind has not disturbed the test field. The **24-hour board** is read and reset daily at the same time as temperatures and total snow depth. It is the basis for the daily water equivalent and new snow depth for weather station records. Next is the **interval board**, which is read frequently throughout each storm. Snow cores are taken from this board for each 10 cm of new snow. The board is cleaned and reset flush with the snow surface after each measurement. Readings from the interval board are plotted against storm duration as part of the storm plot. The fourth and last snowboard, called the **shoot board**, is set flush with the snow surface immediately after the first stabilization attempt during a storm. It serves as a reminder of avalanche regeneration during a prolonged storm or a series of small storms. Information from this board alerts the forecaster to the cumulative precipitation rate curve on the storm plot (see Part I of storm plot, fig. 12).

Weight of the new snow in grams per square centimeter (g cm^{-2}), used in evaluating avalanche hazard on the storm plot, is obtained by taking a snow sample or core. An aluminum, thin-wall, open-ended tube with a 3-inch diameter has proven very satisfactory for these measurements, and is easier to handle than an 8-inch can. The tube should be at least 30 cm long, or roughly equivalent to the maximum new snow depth expected in a 12-hour period. To obtain a snow sample, the tube is thrust vertically through the new snow to the base of the snow board. A wide spatula is inserted between the lower end of the tube and the board so the tube and sample can be lifted out. Contents of the tube are dumped in a plastic bag and weighed. Weight in grams divided by the cross-sectional area of the tube in cm^2 gives the required unit.

4. Stability of New Snow

Depth and stability of unsettled snow in an avalanche track are critical factors in avalanche hazard evaluation that usually determine if a moving avalanche has the potential to reach the runout zone with destructive force. This has direct application in planning the control program and to the work schedules of the maintenance crews responsible for keeping mountain roads open.

While it is not possible to apply a definite standard to the stability of an entire slope, it is possible to locate weak layers in new snow deposits and measure shear strength, which provides useful information on snow stability.

Roch (1951) suggested using the ratio of shear strength to computed shear stress as a stability indicator. His approach was primarily oriented toward determining the equilibrium of slabs in avalanche starting zones. By measuring the shear strength (τ_s) with a shear frame, and computing shear stress (τ) as the resultant of the snow weight parallel to the slope, a stability index (R) is obtained for spot locations in the starting zone. When $R = \frac{\tau_s}{\tau}$ is less than 1, a slope is considered unstable. In this case, $\tau = \omega \sin \theta$ where ω is the vertical component of snow weight and θ is the slope angle.

Roch's stability index has much merit, but it presents some problems when applied operationally under field conditions; it is not practical to obtain such data from avalanche slopes on a 24-hour basis. It is also difficult to use the shear frame in snow with densities greater than 200 kilograms per cubic meter (200 kg m^{-3}).[5] Snow densities in starting zones often exceed 200 kg m^{-3}, and forcing the frame into such snow may cause premature collapse or fracturing. Highly erratic readings result.

Field work with shear frames does provide useful information on snow stability in avalanche tracks, when tests are made on an identified weak layer in new snow at the base station test field. Experience at Rogers Pass has shown that a stability index where (s) is the ratio of the measured shear strength of the weakest layer to its overburden pressure ($s = \frac{\tau_s}{\omega}$), provides a useful operational tool in determining the timing of gunfire. When this value is 0.7 or less, and depth of unsettled snow in avalanche tracks is equal to or greater than 30 cm, the likelihood of avalanche release is good and slides are expected to run the full track distance. This index is readily obtained at the base station test field during storms, day or night. While it is not implied that identified weak layers found at the base station are everywhere present in the entire avalanche area (especially in starting zones affected by wind), presence of such weak layers indicate existence of similar stratigraphic discontinuities in the avalanche tracks.

[5] 200 kg m^{-3} = 0.20 g cm^{-2} = 20 percent.

Field Procedure - Stability Index

There are four basic steps in the field procedure for determining the stability index for soft slabs: (1) determine the depth of unsettled snow, (2) locate the weakest shear plane in the new snow, (3) measure the shear strength of the weakest layer and the weight acting on it, and (4) divide shear strength by snow weight. Work is done at the base station test field. Depth of the unsettled snow is determined with the first section of a ram penetrometer. Hold it vertically between the thumb and forefinger at the 95 cm mark while the tip of the cone touches the snow surface. The ram is released and allowed to penetrate into the snow. The snow layer penetrated by the ram is the layer to be sampled for stability.

A pit is dug to the depth indicated by the penetration test. Snow samples 30 cm by 30 cm and 30 cm deep, are carefully removed from the pit wall with a thin, square, metal cutting plate. The samples are placed on a tilting platform. After the platform is tilted to an angle of 35 degrees, roughly equivalent to the average gradient in avalanche starting zones, a sharp rap on the base of the platform causes shear failure of the weakest layer, so that the top section falls away (fig. 6). Measure the height of the remaining sample and subtract this from the original 30 cm depth for the shear plane location. This procedure is repeated until all of the snow in the exposed wall has been tested. Although more than one weak layer may be

Figure 6.--Tilt-board and snow sample used to determine the location of a weak shear plane in the surface snow layers at the Rogers Pass base station.

found, the weakest one can usually be detected by observing the character of each failure during testing.

Shear strength of the weakest layer is measured in a newly exposed portion of the pit wall with a 100 cm² shear frame (fig. 7). To make this reading:

1. Remove all except the last 4 cm of snow above the shear plane with a spatula.
2. Place the shear frame on the snow above the plane and carefully and slowly press it downward until it rests directly on the weak layer. It is often difficult to place the frame on the weak layer without causing a premature collapse failure on the plane, particularly if the snow immediately above the plane is tough. In such cases, cut through the snow where the shear frame must pass with a sharp, thin-bladed knife before inserting the frame.[6]
3. Hook a 1,000-gram spring balance to the frame and pull steadily in a direction parallel to the weak layer until shear failure occurs (fig. 7).

An average of three readings is taken. Weight of the snow lying above the weak layer can be quickly ascertained by the procedure described earlier for determining the water equivalent of snow on the base station snow boards.

Figure 7.--Using the shear frame in a surface pit. Handle on top of frame allows operator to keep instrument from accelerating after shear failure takes place in hard snow.

[6]Personal communication with Andre Roch, Swiss Fed. Inst. for Snow and Avalanche Res., Davos, Switz.

Test Slope Stability

When significant instability is found ($s < 0.7$), or if there are any doubts about stability in the base station test field, additional work is done on the representative test exposures (fig. 8)—if time and weather permit. Snow deposition on the test slopes is monitored by means of slope stakes (fig. 9), which are cleaned and reset flush with the snow surface following each storm. Bases of these stakes have the same dimensions as the storm boards. The vertical portion of the slope stake is hinged to permit the base to lie parallel to the slope.

Figure 8.--Observers testing surface snow layers at the "Round Hill" test slopes above base station. Trans-Canada Highway in valley 4,000 feet below.

A pit is dug to expose the vertical profile of snow lying above the board, and the pit wall is examined for weak layers. Such layers can be detected by inserting a spatula or a small piece of plastic (about the size of a credit card) vertically

Figure 9.--Slope stake with hinged vertical depth marker in decimeters is used to determine snow loading in the steep starting zone areas of test slopes. Stability data for surface snow layers lying above the base of this board provide useful information on stability of snow at avalanche fracture lines.

at the base of the snow layer and slowly forcing it (with one hand) to cut through to the snow surface above. This is repeated several times until layers with different strengths are delineated. Snow grains in these layers are examined with a 10-power hand lens. Presence of graupel, hoar, degenerated suncrusts, or other loose, cohesionless grains are warning signs of instability, particularly when they appear in defined layers 30 cm or more below the snow surface. Snow grains found in the exposed pit wall are classified according to the physical processes responsible for their formation. Sommerfeld (1969) explains this in his "Classification Outline for Snow on the Ground." Layer thicknesses and height above the sloping snow board are also recorded.

Ram penetration tests made with the new lightweight penetrometer (fig. 10) described by Perla (1969) provide valuable additional data on snow stability, and permit accurate resistance to penetration measurements on low-density snow for the first time. Recent field tests in Utah and Colorado show it is capable of detecting differences in snow strength with densities as low as 70 kg m^{-3}. Ram numbers between 0.1 and 3 kg are measured with ease, whereas measurements with the standard ram were unreliable below 3 kg. The instrument (plus driver) weighs only 200 grams, is easily transported, can be operated by one man, and is quick to use. Procedures for operating the lightweight ram penetrometer follow:

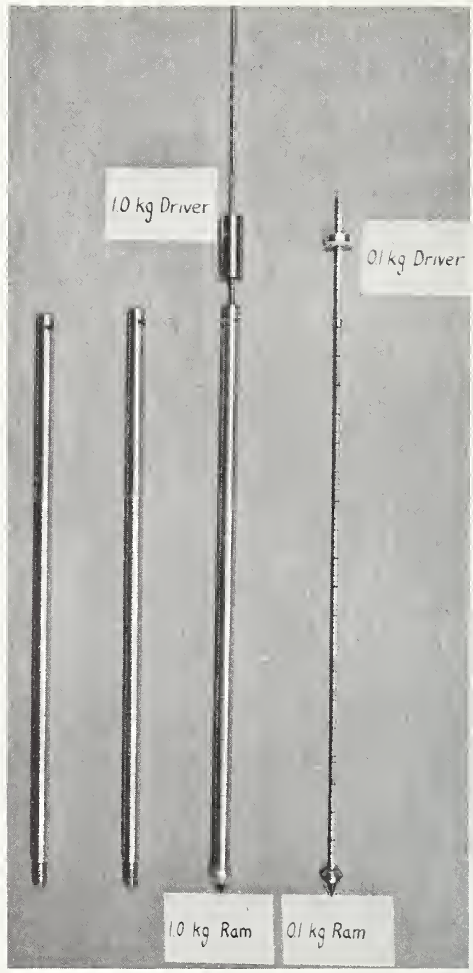


Figure 10.--Standard ram penetrometer with 1 m extensions, left; lightweight ram, right. Both instruments measure resistance to penetration and give an index of mechanical strength of snow.

1. Hold it vertically between thumb and forefinger with the cone tip touching the snow surface.

2. Release, allowing instrument to penetrate into the snow.

3. Read and record depth of penetration.

4. Add the driver, slip it over the guide rod and carefully lower it (while supporting the penetrometer weight with the other hand) until it rests on top of the larger driving shaft.

5. Release, allowing instrument and driver to further penetrate from its position in step 3.

6. Read and record this penetration depth.

7. Raise the driver to the 1 cm mark on the guide rod and release (driver free-falls to top of shaft).

8. Repeat step 6.

9. Repeat step 7.

Steps 6 and 7 are repeated, until the cone reaches harder old snow. Drop height of the driver is increased as needed, and several drops from the same height can be repeated without reading penetration depth, as long as the rate of penetration is uniform and does not exceed 2 cm per drop. Ram numbers (W) are computed, from $W = \frac{Rhx}{d} + R + Q$, where:

R = mass of driver (kg)
h = fall height of driver (cm)
x = number of hammer drops for each (h)
d = net penetration depth
Q= mass of penetrometer (kg)
W= ram number (kg)

Penetration depths in cm are plotted against ram numbers on millimeter cross-section paper, and the points are connected by lines to construct a profile of relative mechanical strength of the layer tested. Changes in snow stability are readily apparent, when such tests are made and plotted at intervals during storms (a 6-hour interval is suggested). Although this instrument has not been operationally tested and is not commercially available at present (the standard 1 kg parent unit, fig. 10, has been available for years), we are impressed with its ease of operation, and believe it to be a worthwhile addition to the limited objective tests currently available to avalanche men in the field.

Test skiing provides further information on slope stability. Presence of tensile stress in soft slabs is detected by observing the reaction of snow in the immediate vicinity of the skis. In the absence of surface crusts, local fractures that extend just 1 or 2 feet in front or to the sides of the skis indicate only slight instability. When such fractures extend many feet from the skis, instability is high and conditions are favorable for avalanche release. Snow is extremely unstable when one is able to release test-slope avalanches merely by approaching them from a distance of 50 to 100 feet above the fracture line.

In lieu of a lightweight ram, the handle end of a ski pole is used to probe test slopes. Presence or absence of well-defined weak layers is felt by changes in the degree of resistance to penetration with depth. In general, moderate to strong resistance to penetration in old surface layers (top 10 to 20 cm), with decreasing resistance with depth, indicates instability. Soft slabs (new snow) will not even support the weight of the pole. Determination of slope stability is an art, and there is no substitute for experience. Best information is obtained by combining astute field observation with numerical data provided by instruments.

A three-man team is recommended for work on test slopes. The most experienced one identifies snow structure at the slope stakes and operates field instruments, a second man records data in a waterproof field book, and the third person anchors and belays the other two with 7/16-inch nylon climbing ropes. Ropes are anchored to a tree or belay post above the test slope. Should the slope avalanche (it often will), the men on it shout: "Falling!" to alert the belayer. Rope diameters less than 7/16 inch are not recommended: forces created on the rope by avalanche snow flowing over the rope and attached man can exceed those developed in a 30-foot free-fall! [7]

Use of a packboard-mounted, lightweight test kit (fig. 11) containing field instruments facilitates data collection and allows observers to move quickly from one test area to another.

---

[7] *Personal communication with Edward R. LaChapelle, Dep. Atmos. Sci., Univ. Wash., Seattle.*

Figure 11.--Packboard-mounted test kit containing instruments for making strength and stability measurements of snow on test slopes.

III. FORECASTING TECHNIQUE—DRY SNOW

5. The Storm Plot[8]

The storm plot is used to determine the timing of gunfire and the sequence of control operations. It consists of a three-part graphic display of the field data gathered during storms (fig. 12). Part I establishes a relationship between precipitation intensity, cumulative new snow weight, and avalanche occurrence; Part II depicts temperature and wind; and Part III illustrates snow stability, depth of the unsettled snow, and avalanche occurrence.

Part I. The Control Curve

This section of the storm plot utilizes past records of precipitation intensity and avalanche occurrence to predict the onset of current avalanche activity. The control curve depicts cumulative new snow weight as a function of time (fig. 12, Part I). The slope of the curve represents the average cumulative precipitation rate during storms that produce natural avalanching. Critical weight levels for avalanche release are identified on the curve.

At least 5 years of data on precipitation and natural avalanches are needed before a reliable control curve can be made. Twelve-hour precipitation amounts and hourly avalanche release times are used to construct the curve.

The first step in constructing the control curve is to select each storm that caused natural avalanches to approach or block the highway. Plot cumulative new snow weight in g cm^{-2} against storm duration in hours. Make a curve for each storm by connecting the points. Place arrows on each curve to indicate the release time of each avalanche. Identify each snow slide by either entering an abbreviation or a number alongside each arrow. When all data are plotted, fit the control curve (by eye) as an average of the individual curves.

Critical weight levels are now marked on the control curve. Select the earliest avalanche release time (the arrow nearest the Y axis), and extend this arrow vertically until it intersects the control curve. With a pencil, follow the control curve to the left (toward its point of origin) for a distance equivalent to 4 hours on the X axis. Clearly mark this point with a large arrow. **The new snow weight corresponding to this point is the critical weight.** Artillery control should begin when the new snowfall reaches this weight. The 4-hour lead time is used as a safety factor; it allows time to mobilize gun crews in advance of expected avalanche activity, and provides leeway needed to allow peak traffic flows to clear avalanche areas.

The precipitation and avalanche data plotted for Rogers Pass, Canada, showed three distinct avalanche groupings. Avalanches in group I fell during the latter part of the first 24 hours, group II fell between 40 and 50 hours, and group III fell from

---

[8]*The storm plot was originally conceived by Montgomery M. Atwater to monitor winter storms and avalanche potential at Alta, Utah. Principal modifications in the author's version include the control curve, critical weight concepts, and the stability index.*

84 to 96 hours after storms began. Although there was some overlapping of groups, the avalanche pattern was sufficiently distinct to warrant identification of a critical weight for each group:

Avalanche frequency group	Critical weight g cm^{-2}	Hours since storm began
I	2.5	20
II	3.6	36
III	5.5	80

The existence of three avalanche frequency groups at Rogers Pass was a lucky find, because it simplified the control job. Crews could concentrate on the most sensitive avalanches in the early stages of a storm, and did not have to worry about the 50 avalanches in groups II and III until later (there were 80 avalanches in 27 miles of the three-lane road).

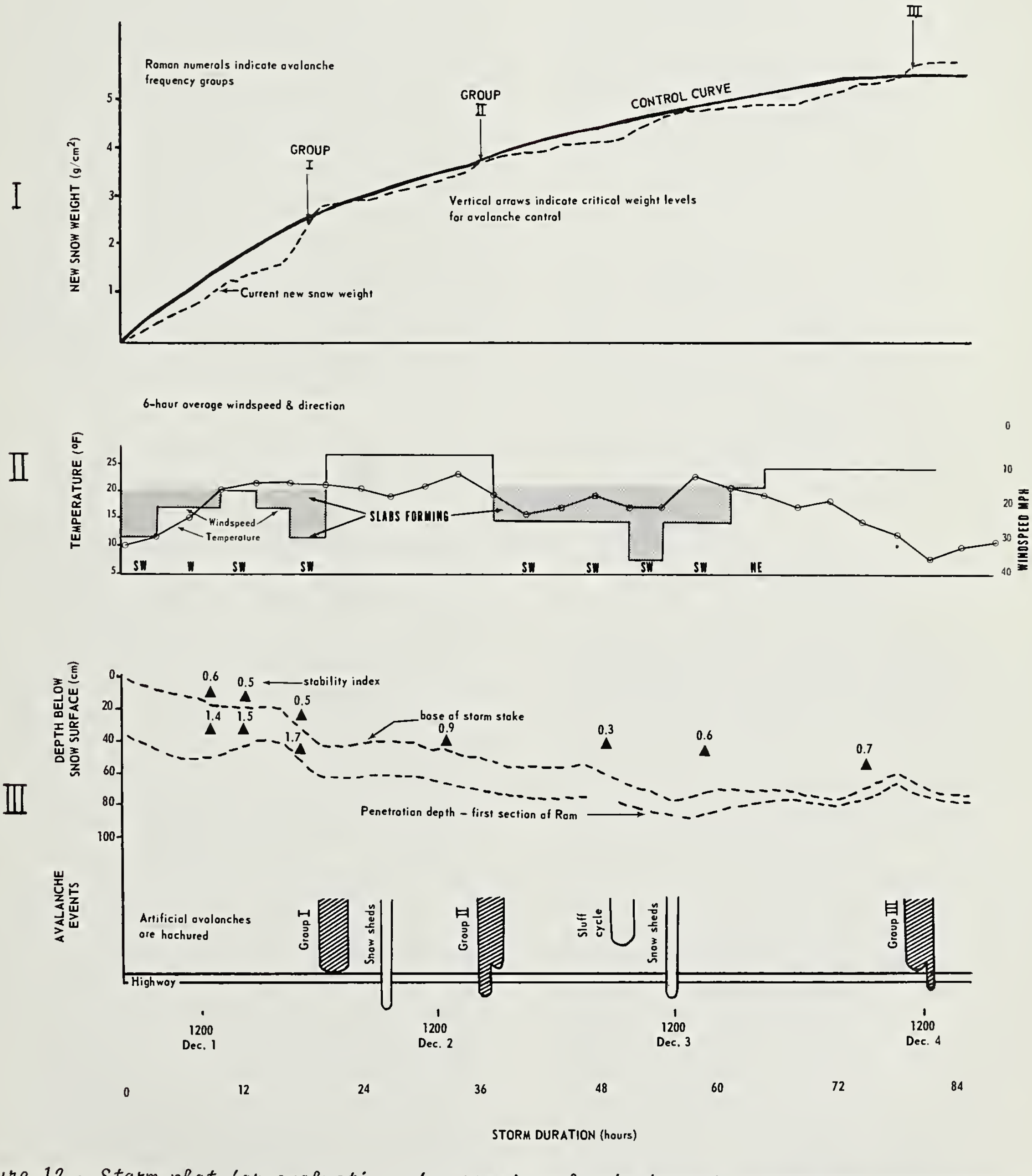


Figure 12.--Storm plot for evaluation of current avalanche hazard. Field data on weather, snow and avalanches are plotted and kept current during storms.

A good deal of scatter was found when this plotting technique was applied to data from Berthoud and Loveland Passes in Colorado. Avalanches did not appear in well-defined frequency groups, although the onset of slide activity during large storms was well defined. Stratification of the Colorado data into low-intensity and high-intensity storms produced critical weights of 2.7 g cm^{-2} in 46 hours and 2.2 g cm^{-2} in 16 hours for the respective types (fig. 13). Low-intensity storms averaged 0.02 inch water equivalent per hour (in hr^{-1}) and high-intensity storms averaged 0.05 in hr^{-1} for this set of data. Light snow fall, and the combination of high wind and expansive flat areas above timberline upwind from starting zones (all of which favor heavy transport) add to the scatter in the Colorado data.

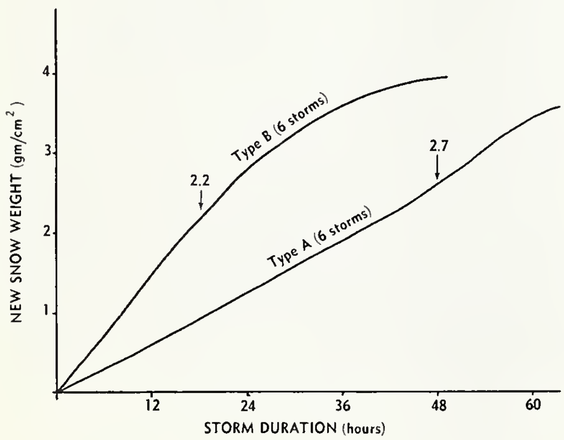


Figure 13.--Control curves for determining onset of avalanche control measures for low (type A) and high (type B) intensity storms. Data for Loveland and Berthoud Passes in Colorado.

Another factor which prevented a valid test of avalanche frequency response to cumulative new snow weight in the Berthoud and Loveland Pass data was the constraint of having to use natural avalanches that occurred between control applications applied by the Colorado Highway Department. Such control applications, even though not rigorously applied, do affect avalanche response. Also, large storms that are required to produce the less frequent avalanches in groups II and III on the control curve are rare events in this section of Colorado (Judson 1965). The authors feel that Part I of the storm plot, the control curve, is most applicable in areas where average precipitation intensities during avalanche-producing storms exceed 0.05 in hr^{-1}. Winter precipitation intensities equal to or greater than 0.05 in hr^{-1} are common at the following highway avalanche areas: Alta, Utah; Red Mountain and Wolf Creek Passes in Colorado; Granduc Mine and Rogers Pass, British Columbia. The control curve is, nonetheless, a useful aid in planning control programs even in low-intensity precipitation areas such as Colorado's Berthoud and Loveland Passes.

The control curve and critical weight levels are etched on a piece of stiff transparent plastic, which is used as an overlay for current storm plots of cumulative new snow weight against storm duration. New snow weights are plotted for each 10 cm of new snow from the base station interval stake during storms. Special attention is given to the rate at which the cumulative new snow weight approaches each critical weight level on the control curve, for this determines whether the decision to start control must be initiated prior to or at some time later than the time indicated by the frequency-group arrows. Information from the two other parts of the storm plot must also be considered at this point before any decisions are made.

Part II. Temperature and Wind Limitations

Wind and temperature during a major storm influence the amount and type of snow deposited in starting zones. Experience at instrumented avalanche stations shows that winds between 15 and 30 m.p.h., when accompanied by new snow and temperatures between 10° F. and 30° F. often cause widespread formation of unstable soft slabs (stippled area, fig. 12, Part II) in avalanche starting zones. Presence of soft slabs favors avalanche release by artillery because they have (1) a high degree of internal cohesion, and (2) relatively high stress concentrations, which allow rapid propagation of fractures initiated by explosives.

Six-hour averages of windspeed, wind direction, and temperature from remote stations are plotted in Part II of the storm plot. Wind direction during storms is also important because it determines what slopes will receive snow deposition. During some high-intensity snowfalls, slabs form on all slopes, regardless of wind direction or slope orientation. Such conditions occur from combination falls of rimed spatial dendrites, needles, and graupel. LaChapelle's (1969) Field Guide, written especially for avalanche men, presents excellent illustrations

of new snow crystals. We recommend this book.

Part III. Track Stability, Snow Depth, and Avalanche Occurrence

Data from stability tests made at the base station and on the test slopes are utilized in this section, along with snow depth and avalanche occurrence. New snow depth read from the storm board, and total depth of the unsettled track snow determined by penetration tests, are plotted against storm duration. Stability indexes, shown above the triangles on figure 15, are plotted to show the location of the weakest layer in relation to the snow surface. The total depth of unsettled snow, determined by the penetration depth of the first section of the ram, gives the amount of track snow that is likely to become incorporated in a moving avalanche.

All natural and artificial avalanches of any significance are plotted at the bottom of the storm plot to show the location of avalanche debris relative to the highway.

6. Using the Storm Plot

The total storm plot, with all three parts, can only be used as an aid in determining when to initiate control action during major storms, for it was designed for use in situations involving direct-action soft-slab avalanches. At a glance of the forecaster's eye, it gives an instant summation of the current avalanche potential and a summary of events leading to the current situation—something not possible by memory alone. Successful implementation still depends heavily on experience and intuition because many variables known to affect avalanche release are extremely difficult to measure under field conditions. Every avalanche man knows that conditions days, weeks, or even months prior to the onset of a major storm will affect the response of avalanches to a given storm. The availability of an unbroken and detailed record of weather and snow conditions affecting the control area prior to each storm is therefore essential.

Parts II and III of the storm plot can be used without modification at most avalanche areas in North America. The shape of the control curve and the critical weight levels (Part I) for determining the onset of avalanche control operations will change from one area to another. For instance, control curves for avalanche areas along the West Coast are expected to reflect the higher precipitation intensities associated with winter storms there in contrast to relatively low intensities found in the mountains of northern Colorado and Wyoming. The degree to which these differences will affect placement of critical weight arrows remains to be seen. It is worth noting that precipitation amounts given by Atwater (1952), Poggi and Plas (1966), and Judson (1967)—which initiate widespread avalanching in Utah, the French Alps, and the Colorado Rockies, respectively—coincide with the 2.5 g cm^{-2} weight level on the Rogers Pass storm plot. On the basis of these data, one can reasonable assume that the first critical weight level for sensitive avalanches (Group I) at most areas will be in the vicinity of 2.5 grams.

The situation for releasing avalanches by artillery fire is ideal when (1) cumulative new snow weight in Part I of the storm plot approaches or exceeds the control curve at the critical weight levels indicated by the arrows, (2) conditions specified in Part II are met, (3) snow stability in Part III is ≤ 0.7, and (4) unsettled track snow is ≥ 30 cm. If critical weight levels are reached or approached prior to the time indicated on the control curve, artillery control is initiated earlier than indicated; for lower precipitation rates, gunfire is delayed.

Special Cases

Snow accumulating in either catchment basins or avalanche tracks prior to onset of a major storm will influence the timing of control action for all avalanche groups unless this snow is stabilized by settlement. Results of test skiing (U. S. Forest Service 1961) plus an analysis of the surface snow layers on the test slope stakes determines what timing adjustments are required. Recognizable remnants of new snow crystals such as stellar arms and thin platelike fragments, or presence of small needlelike splinters indicate a lack of stabilization. If there is still unstable snow on the slopes at the onset of a major storm, the total weight of snow considered unstable on the slope stakes is added to the snow weight for the present storm. Avalanches are controlled when the total snow weight equals the critical weight levels for each group (Group I = 2.5 g, etc.).

If a storm terminates before the new snow weight reaches the critical weight levels of the second or third avalanche groups, it is necessary to control Groups II and III before settlement occurs.

The chances of releasing most of these slides still remain high, although it is unlikely they will run the full length of their tracks.

A very dangerous avalanche situation arises when soft slab forms in the absence of wind, because all exposures are affected. This condition is initiated by a fall of pure needle crystals, rimed spatial dendrites, or graupel, after the accumulation exceeds 15 cm. Astute observation of new snow crystals and of surface snow reaction to test skiing during such storms is necessary. Deep falls of loose snow composed of clustered dendrites, plates, or stellar or irregular crystals usually do not result in initial soft slab avalanches if these crystals fall when windspeeds are less than 12 to 15 m.p.h. After new snow depth approaches or exceeds 60 cm., however, avalanches composed of loose snow may be expected. Hazard develops quickly in this situation with an increase in windspeed, even after snowfall has ended. Artillery fire should commence within 2 hours following an increase in wind if the new snow weight approaches or exceeds any of the critical weight levels.

Gusty winds in excess of 30 m.p.h. create erratic deposition patterns. Snow transported away from the usual fracture-line positions is deposited only in the most sheltered areas. In such cases, projectiles are fired into the lower portions of the starting zones and in upper sections of the avalanche tracks in addition to the regular targets.

Similar target adjustments may be required during storms when temperatures are above 25° F. and windspeed is marginal (12-18 m.p.h.), particularly when the starting zone is exposed to sun for an hour or two prior to artillery fire. Projectiles are fired into areas below the normal release points in these cases. Experience shows best results are obtained when shots are placed in shaded steep sections of the track.

Extremely low stability indexes (s = 0.2-0.4) in the track snow dictate early artillery control, otherwise large volumes of snow reach the highway due to the increased descent speed of the avalanches. Such low stability indexes are sometimes caused by weak layers of surface hoar, pure graupel, or other loose, cohesionless grains such as depth hoar.

Rain on snow is a unique case precluding use of the storm plot, particularly when rain falls on fresh, cold snow. If special weather forecasts give adequate warning, shoot every target in the control area before the rain begins.

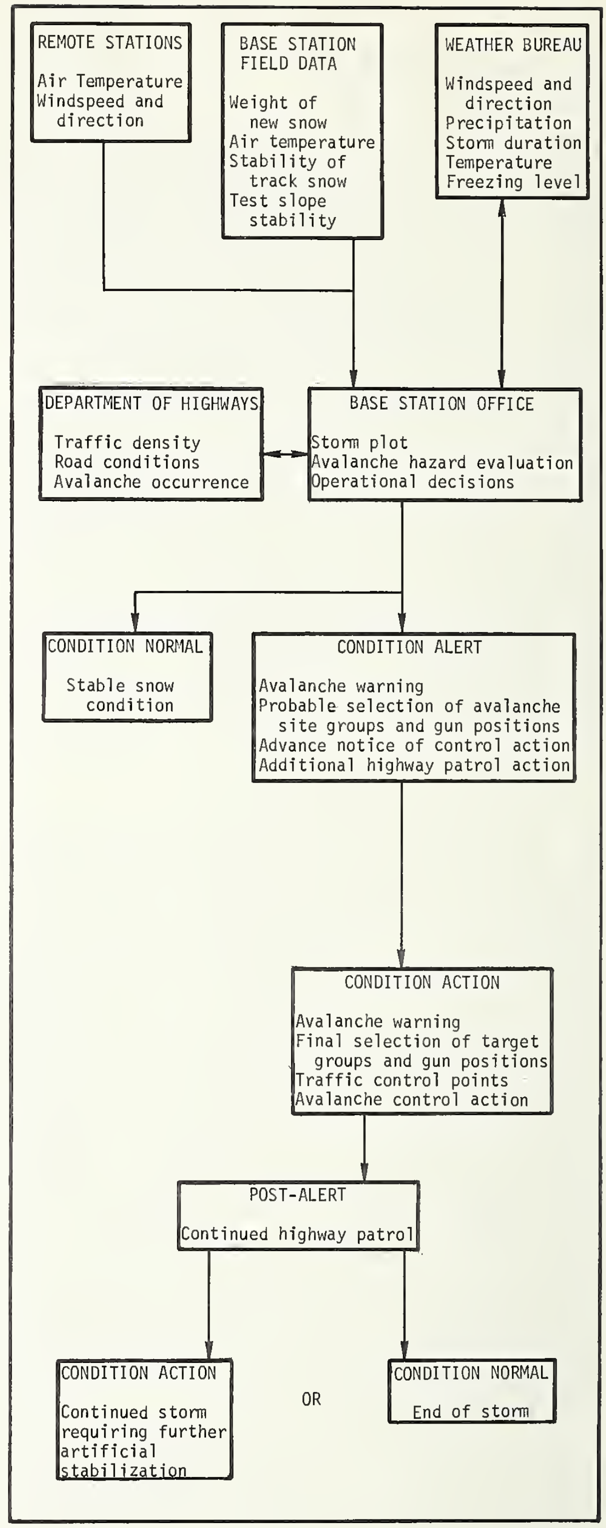


Figure 14.--Operations flow chart of the avalanche forecast unit at Rogers Pass, British Columbia.

7. Issuing the Forecast

Farecasts are issued an the basis af infarmatian fram the latest available mauntain weather fare-cast, the starm plat, and the highway patral's esti-mate af traffic density (fig. 14).

Weather Forecasts

A reasanably accurate mauntain weather forecast is needed befare an avalanche hazard farecast is issued. Weather forecasts can be received fram any af the main Weather Bureau farecast centers such as Vancauver, Seattle, San Francisca, Calgary, Salt Lake City, or Denver. Weather farecasts shauld be received every 12 haurs, and shauld cantain the fallawing infarmatian:

1. A general summary af current synapticconditians.
2. Duratian and intensity of expected precipitatian.
3. Windspeed and directian in the free air at a level within 1,000 feet af most af the starting zanes in the cantral area.
4. Expected temperatures at starting-zane elevatians.
5. Elevatian af freezing levels (there is aften mare than ane).
6. A repart af starm behavior at mauntain statians upstream alang the starm track.

Befare the Weather Bureau farecast centers can issue their farecasts, they need the fallawing obser-vatians fram the mauntain every 12 hours:

1. State af weather: claudy, partly claudy, snaw, snaw flurries, etc.
2. Height af claud base and trend (rising, na change, lawering).
3. Maximum, minimum, and current temperature, and dew paint.
4. 12-haur precipitatian—bath water equivalent and new snaw depth.
5. Precipitation intensity and trend.
6. Windspeed and direction during the past 6 hours from the remote stations.
7. Pressure tendency.

Weather Bureau personnel are not normally charged with the respansibility af making mountain weather forecasts, but they will, if requested. Such farecasts are very difficult to make because of the scarcity of reparting stations in the mountains and the lack of farecasters familiar with mountain weather canditions. Daily contact with weather forecasters will help improve farecasts. When possible, these men shauld be braught to the mauntain station where forecasts are needed. Mutual problems can be discussed, and the weather farecaster can gain useful backgraund infarmatian by seeing instrument lacatians and terrain.

Althaugh teletype, telephane, ar radia-telephane can be used far communicatians with the nearest farecast center, teletype services are recammended because a permanent recard af all transmissians is readily available, and farecasts can be transmitted ta the base station when observers are aut an other jabs. A radio-telephane serves as a backup when land lines are out af service during and fallawing severe starms.

Traffic Density

Peak traffic flaws usually fallaw in same recag-nizable pattern which can be anticipated in advance. Since cangested periads seldam last more than 2 haurs, it is aften passible ta delay cantrol wark until traffic peaks pass the avalanche area. This minimizes the number af peaple affected by tem-porary raad clasures, and simplifies traffic cantral during stabilization programs. Because critical weight levels on the cantral curve are placed 4 haurs priar ta the first avalanche event, there is same leeway ta allaw far periads af heavy traffic. Peak flows are anticipated by cantacting state palice and highway maintenance crews far a distance af 100 miles on either side af the cantral area. Snawfall intensity, wind, temperature, and snaw stability dictate haw much leeway the farecaster has.

Format, Forms, and Dissemination of the Forecast

Cantral decisians far actian and safety measures are written clearly and concisely at the base statian an standard farms. This infarmatian is transmitted by phane ar radia-telephane ta highway maintenance persannel respansible far carrying aut cantral; they, in turn, write the infarmation on identical forms at the headquarters maintenance statian. This infor-mation should be read back to the base station word-for-word, to make sure the correct information has been received. Color-coded forms, each repre-senting a specific type of farecast, are recommended to avoid canfusion. We refer to the forms as: ALL-CLEAR, ALERT, and ACTION.

An ALL-CLEAR is issued when snow conditions are stable. It enables maintenance men to plan ahead for jobs requiring men and heavy equip-ment that might otherwise be tied up in standby or avalanche-clearing operations.

The ALERT form is issued several hours prior to anticipated highway closure. It warns of a mounting avalanche hazard, and shows when and where artillery will be used. In addition, the ALERT form notifies maintenance crews when extra patrol action is needed, and when snow removal is required at gun sites. The type of weapon to be used and the number of shells needed are also specified.

The ACTION form is issued about 1 hour before the gun should go into action, which is sufficient time to ready previously alerted gun crews. An evaluation of the prevailing avalanche hazard is posted at the same time, and the location and sequence of traffic blocks is laid out so all danger zones will be clear of traffic and snowplows during the stabilization program. The sequence of gun positions is outlined and traffic clearing periods are indicated. What gun or guns are to be used is given as well as the number of rounds of ammunition required.

After the first stabilization program is completed during continuous storms, the ALERT form is again issued to show the reduction of avalanche hazard. The required weapon and likely gun positions are again stated when another action period is anticipated. An ALL-CLEAR is issued when the storm subsides and the stabilization program is considered successful.

IV. CONSIDERATIONS FOR WET SNOW AVALANCHES

Wet snow avalanches present a special problem for highways because artillery control is generally ineffective unless soft slab is present. In both Canada and the United States, gun crews confirm the fact that explosive control measures applied to wet snow seldom produce results. There are two possible explanations: (1) isometric grains in a wet snowpack suppress shock wave propagation due to their large grain size and the lack of intergranular bonding; and (2) rapid creep in isothermal snow quickly relieves stresses and prevents dangerous slab conditions from developing.[9] Wet-slab avalanches do occur under natural conditions, however. Regardless of the character of release (loose or slab), wet slides of major proportions present a difficult snow removal problem because they penetrate to the ground and deposit large amounts of mud, rocks, and trees on the highway. Forecast bulletins warning of impending hazard are the only safeguards.

Rain falling on cold, fresh snow is the most common cause of wet avalanches in winter. Presence of an impermeable layer beneath the new snow accentuates the problem; dangerously unstable conditions develop when the snow becomes saturated and the layer is lubricated. Data on the amount of rain needed to initiate avalanches under these conditions are scarce, but forecasters at Squaw Valley, California, feel at least 1 inch is necessary.[10] Recent data from stations in western Washington tend to confirm the 1-inch value as a minimum.

Rain affects snow in several ways: it reduces strength by weakening intergranular bonds, increases density and weight, and warms snow to 0° C. Because warming is a general requirement for wet slides, temperature profiles in surface layers indicate approaching hazard. Current avalanche activity is the most reliable guide to hazard conditions. This information is radioed to the base station by highway maintenance patrols. Information on expected changes in the freezing level (in the free air) provided by the Weather Bureau is also needed.

In spring, large wet avalanches may occur when the entire snow cover from the midtrack level to the valley floor is warmed to 0° C. and snow depth in the track is greater than 1 m. Progressive warming of the snow cover should be monitored by digging full-depth pits and taking temperature profiles at the midtrack level. South exposures are checked first. Minimum temperatures are found in the middle of the pack, as heat is being added to lower layers from the soil and to the upper layers by radiation. When snow becomes isothermal at 0° C. at the midtrack level on south exposures, additional temperature profiles are taken on east, west, and north exposures in that order.

Snow conditions in the first meter below the snow surface signal the onset of wet avalanches after snow becomes isothermal. A fall of new snow, 25 cm. or more in depth, often causes wet slides. If soft slab is present in starting zones (determined by checking test slopes), artillery con-

---

[9] *Personal communication with Edward R. LaChapelle, Dep. Atmos. Sci., Univ. Wash., Seattle.*

[10] *Personal communication with Richard M. Stillman, Rocky Mt. Region, USDA Forest Serv., Denver, Colo.*

trol is used. The sequence of control is based on snow conditions at the test slopes and in the avalanche tracks. For instance, if soft slabs are found on east exposures and snow cover (to the ground) is isothermal only on south-facing tracks, then avalanches with east-facing starting zones and south-facing tracks are shot first. If soft slabs are present everywhere, control priority is based on frequency groups on the control curve—the same as in winter. The worst situation arises when a deposit of new snow fails to "slab up"—if followed by a warm, suuny day. The strong input of heat often releases avalanches, and because the track snow is isothermal, much, if not all, of it will be incorporated in the flow. Large quantities of avalanche snow reach the highway in such cases.

Wet avalanches may also occur in old snow when an ice layer, 30 cm or more below the surface, acts as a dam to the intrusion of melt water. Saturation of the large-grained old snow above the ice layer leads to avalanching, particularly in the absence of a strong surface crust. Such crusts usually form overnight, and disintegrate in the morning due to heating. A relationship between the deterioration of such crusts (when a buried ice layer exists with saturated snow resting on it) and the onset of spring avalanches was developed from the early studies at Rogers Pass:

1. No surface crust. Avalanches start as early as 0800 hours on southeast exposures, 1000 hours on south exposures, 1200 hours on southwest exposures, and 1700 hours on west exposures.

2. Moderately strong surface crust, 3 to 5 cm. thick. Resistance to penetration 2 to 4 kg (may break when a person walks on it). Avalanches on southeast exposures may begin at 1000 hours. Most avalanches fall between 1130 and 1500 hours on southeast, south, and southwest exposures. Some avalanches are expected on west-facing slopes until 1800 hours.

3. Strong surface crust, 8 to 14 cm thick. Resistance to penetration 6 to 10 kg. (will support a person). Avalanches are unlikely before 1400 hours, and then with only moderate frequency and only on south and southwest exposures.

Deterioration of surface crusts, when present, should be checked at 2-hour intervals beginning at 0700. A warning is issued when the effective thickness of surface crusts decreases to 5 cm. (avalanches begin when the crust disintegrates).

The best deterrent to the large, wet avalanches of spring, is a rigorously applied and carefully planned control program during winter to reduce snow depth in the tracks.

Literature Cited

Atwater, M. M.
1952. The relationship of precipitation intensity to avalanche occurrence. West. Snow Conf. Proc. 20: 11-19, illus.

Frutiger, Hans.
1964. Snow avalanches along Colorado mountain highways. U.S. Forest Serv. Res. Pap. RM-7, 85 p., illus. Rocky Mt. Forest and Range Exp. Sta., Fort Collins, Colo.

_______ and Martinelli, M., Jr.
1966. A manual for planning structural control of avalanches. U.S. Forest Serv. Res. Pap. RM-19, 68 p., illus. Rocky Mt. Forest and Range Exp. Sta., Fort Collins, Colo.

Judson, Arthur.
1965. The weather and climate of a high mountain pass in the Colorado Rockies. U. S. Forest Serv. Res. Pap. RM-16, 28 p., illus. Rocky Mt. Forest and Range Exp. Sta., Fort Collins, Colo.

____
1967. Snow cover and avalanches in the high alpine zone of western United States. In Physics of Snow and Ice, Int. Conf. Low Temp. Sci. [Sapporo, Japan] Proc. 1966: 1151-1168, illus.

____
1969. A pilot study of weather, snow, and avalanche reporting for Western United States. Sixth Conf. on Snow and Ice [Calgary, Alberta, Canada. Oct. 23-24, 1969.] Proc. (In press)

LaChapelle, Edward R.
1969. Field guide to snow crystals. 101 p., illus. Seattle: Univ. Wash. Press.

Mellor, Malcolm.
1968. Avalanches. Cold Regions Science and Engineering. Part III: Eng., Sect. A3: Snow Technology. U.S. Army Materiel Command, Cold Regions Res. and Eng. Lab., 215 p., illus. Hanover, N. H.

Neal, G.
1962. Automatic telemetry equipment aids avalanche prediction. Can. Electronics Eng. 6(4): 40-43, illus.

Perla, R. I.
1969. Strength tests on newly fallen snow. U.S.D.A. Forest Serv. Res. Note RM-150, 12 p., illus. Rocky Mt. Forest and Range Exp. Sta., Fort Collins, Colo.

Poggi, A., and Plas, J.
1966. Conditions meteorologiques critiques pour le declenchement des avalanches. In Int. Symp. Sci. Aspects of Snow and Ice Avalanches. Int. Union Geod. and Geophys., Int. Ass. Sci. Hydrol. Comm. Snow and Ice Pub. 69, p. 25-34, illus.

Roch, Andre.
1951. On the study of avalanches. Sierra Club Bull. 36(5): 88-93, illus.

Schaerer, Peter [A.]
1962a. Avalanche defenses for the Trans-Canada Highway at Rogers Pass. Div. Build. Res. Tech. Pap. 141, (NRC 7020), 35 p., illus. Nat. Res. Counc., Ottawa, Canada.

———
1962b. The avalanche hazard evaluation and prediction at Rogers Pass. Div. Build. Res. Tech. Paper 142, (NRC 7051), 32 p., illus. Nat. Res. Counc., Ottawa, Canada.

Sommerfeld, R. A.
1969. Classification outline for snow on the ground. U.S.D.A. Forest Serv. Res. Pap. RM-48, 24 p., illus. Rocky Mt. Forest and Range Exp. Sta., Fort Collins, Colo.

U.S. Forest Service.
1961. Snow avalanches: A handbook of forecasting and control measures. U.S. Dep. Agr. Handb. 194, 84 p., illus.

APPENDIX A

STORM PLOT AND NOTES ON A SEVERE STORM

The following information is presented for persons or agencies who are now, or soon will be, charged with the responsibility of operating an avalanche control program where numerous avalanches, falling from several aspects, affect major highway travel. Artillery control of avalanches at such areas is a complicated matter that requires an organized program and a well-trained forecast staff. A three-man team (two professionals and one technician) is considered the absolute minimum for the forecast unit. The man in charge should have at least 5 years' experience with snow and avalanche forecasting. Preferably, he should have a background in synoptic meteorology, snow physics, and hydrology. His assistant should have at least 3 years' experience in avalanche hazard forecasting and control. A background in hydrology or glaciology is desired. All three men should be competent ski mountaineers. The technician should be sufficiently trained in electronics and instrumentation to install, troubleshoot, and repair all instruments required on the project.

Figure 15 presents a storm plot made at Rogers Pass during a severe and prolonged storm which lasted 156 hours. Forecasts issued during the first 24 hours of this storm are reproduced here to serve as an example of the program in action:

Storm start: 0600 hours January 26

0700 January 26: Forecast FORM ONE (ALL-CLEAR) issued to indicate no expected avalanche activity for at least 12 hours. Forecast from Vancouver Weather Office calls for light snow.

1900 January 26: Storm increases in intensity. Weather forecast indicates snowfall to continue for several hours. Avalanches not expected for 2 more hours (see extension listed on Forecast FORM ONE), based on control curve data.

2100 January 26: Continued heavy snow (see cumulative snow weight and control curve) with wind, temperature, and track snow stability favorable for avalanches, prompts a forecast (ALERT) that control of Group I avalanches will be necessary by 2400 hours or shortly thereafter.

0030 January 27: Storm continues unabated. FORM THREE (ACTION) is issued for artillery control to commence in 1 hour.

0330 January 27: Temporary letup in snowfall occurs but weather forecast calls for storm to continue. Increasing wind with track stability index very low indicates control of Group II avalanches will be necessary before the critical weight for that group is reached.

0700 January 27: Very low stability index of 0.4 with increasing wind and snow at favorable temperature results in decision to control Group II slide at 0800 hours.

1200 January 27: Good stabilization has been achieved within control area. Decrease in wind and increase in track snow stability indicates only low to moderate hazard for the next 30 hours.

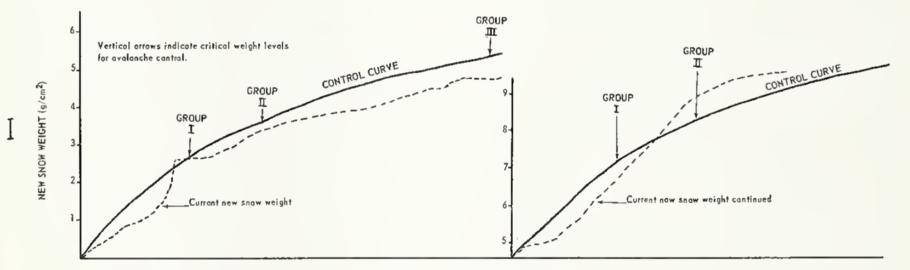


Figure 15.--Storm plot of a severe winter storm at Rogers Pass in 1965. Graphic display of incoming data aids in making avalanche and traffic control decisions along a 27-mile stretch of the Trans-Canada Highway through the Selkirk Mountains.

(FORM ONE)

A L L - C L E A R

ISSUED AT 0700 HRS January 26
(Date)

ISSUED BY Noel C. Gardner

RECEIVED BY R.A. Smith

For the next 12 hours it is not expected that high level snow conditions will produce avalanche activity effective to the highway, nor is artificial stabilization indicated during the interval given above or periods of extension listed below.

EXTENSIONS

Issued at	For approx.	Received by
1900 hrs.	2 hrs.	
hrs.	hrs.	
hrs.	hrs.	
hrs.	hrs.	
hrs.	hrs.	
hrs.	hrs.	

(FORM TWO)

A L E R T

ISSUED AT 2100 HRS January 26
(Date)

ISSUED BY Noel C. Gardner

RECEIVED BY R.A. Smith

1. AVALANCHE WARNING

Minor Dry Avalanche activity is expected within the next 6 hours.

2. EXTRA HIGHWAY PATROL IS REQUIRED BETWEEN:

MILEAGES: 10 mi. and 14 mi.

3. ARTILLERY FIRE MAY BE REQUIRED BETWEEN:

2400 January 26 hrs. and 0400 January 27 hrs.

4. GUN POSITIONS LIKELY TO BE REQUIRED ARE:

2, 3, 8

(FORM THREE)

A C T I O N

ISSUED AT 0030 HRS January 27
(Date)

ISSUED BY Noel C. Gardner

RECEIVED BY R.A. Smith

1. ARTILLERY FIRE SHOULD COMMENCE AT: 0130 hrs. January 27
(Date)

2. ARTILLERY PIECE AND AMMUNITION REQUIRED:

105 mm Howitzer X and 15 Rounds

75 mm Howitzer ___ and ___ Rounds

3. PROGRAM:

GROUP NO.	PONDING SITE	TRAFFIC DELAY	GUN POSITION
1	1 + 2	40 mins.	2 + 3
	2 + 3	20 Mins.	8

4. ACTION:

GUN POSITION	AVALANCHE SITE	TARGET	REMARKS
2	14	1	Avalanche 1/2 path
		2	Detonation heard
3	15, 16	1	" "
8	37	2	Avalanche to edge of highway.
	38	3	Avalanche to within 100' of hwy.

(FORM TWO)

A L E R T

ISSUED AT 0330 HRS January 27
(Date)

ISSUED BY Noel C. Gardner

RECEIVED BY R.A. Smith

1. AVALANCHE WARNING

Reasonable stabilization has been achieved. The likelihood of minor avalanche activity at sites as yet uncontrolled remains.

2. EXTRA HIGHWAY PATROL IS REQUIRED BETWEEN:

MILEAGES: ________ mi. and ________ mi.

3. ARTILLERY FIRE MAY BE REQUIRED BETWEEN:

0600 hrs. and 1200 hrs.

4. GUN POSITIONS LIKELY TO BE REQUIRED ARE:

2, 3, 4, 5, 6, 8

(FORM THREE)

A C T I O N

ISSUED AT 0700 HRS January 27
(Date)

ISSUED BY Noel C. Gardner

RECEIVED BY R.A. Smith

1. ARTILLERY FIRE SHOULD COMMENCE AT: 0800 hrs. January 27
(Date)

2. ARTILLERY PIECE AND AMMUNITION REQUIRED:

105 mm Howitzer X and 25 Rounds

75 mm Howitzer ___ and ___ Rounds

3. PROGRAM:

GROUP NO.	PONDING SITE	TRAFFIC DELAY	GUN POSITION
2	1 + 2	50 min.	2
	2 + 3	1 hr. 5 min.	4
			3
			5
			6
	3 + 4		8

4. ACTION:

GUN POSITION	AVALANCHE SITE	TARGET	REMARKS
2	12	2	Detonation heard
		3	Sound of avalanching snow
4	17	1	Detonation heard
		2	Avalanche into mound defenses
4	17	3	Detonation heard
		4	" "
3	12	1	" "
	12	2	Avalanche within 300' of hwy.
	10	1	" " 100' " "
	10	2	Detonation heard
5	20	3	" "
	20	4	Avalanche within 200' of hwy.
6	23	2	" " 400' " "
	24	1	Detonation heard
	25	2	" "
	26	1	" "
	28	1	Avalanche within 400' of hwy.
8	32-35	all	Small slides, stopped above hwy.

APPENDIX B

INSTRUMENTATION

Numerous instruments needed for avalanche work have been field tested at avalanche stations in the mountain west. The essential instruments are listed here, along with a commercial model of each that has proved reliable under typically severe field conditions.[11]

I. WINDSPEED AND DIRECTION

A. ANALOG SYSTEM

Item	Source
1. Windspeed transmitter F420-C, modified for recording. 4.0 valts D.C. at 100 m.p.h. and linear.	Electric Speed Indicator Co. . 12234 Triskett Road Cleveland, Ohio 44111
2. Wind direction transmitter F420-C-2, modified for recording on twin-channel recarder with 1400 ohms internal resistance.	Do.
3. Power supply and circuitry for recarding vane. 5.0 volts D.C. output.	Da.
4. Esterline Angus Madel A602C twin-channel recorder. Portable case with No. 2 hand-wound spring chart drive, hour and minute feed. Scale 0-1 mil. each side.	Lacal Esterline Angus Distributar
5. Inkwells for 31010B Model No. 14616-2 red and green ink. Order 3 spares.	Lacal Esterline Angus Distributor
6. 24 Esterline charts Na. 31010B, 1 1/2 inches per hour with scale 0-100 left side and 0-150 right side.	Do.

B. CONTACT SYSTEM

Item	Source
1. Totalizing anemometer, Belfort Catalag No. 5-349A. 24 volts D.C. Max. 0.5 amp. One mile and 1/60 mile contacts.	Belfort Instrument Co. 4 North Central Avenue Baltimare, Maryland 21202
2. Wind direction transmitter (less vane) with universal bearing. Belfort Catalog No. 5-363. U.S. Weather Bureau Spec. No. 450.6112. 8 contacts. Max 3 amp. at 25 volts D.C.	Do.
3. Pintle for mounting anemameter	Do.
4. Electric speed indicator spread-tail vane - W.D.V.-400-1C. U.S. Weather Bureau Ser. No. S/N F012. Fits Belfort assembly.	Electric Speed Indicatar Co. 12234 Triskett Road Cleveland, Ohio 44111
5. Power supply specs. for anemometer and vane: Regulated, variable 0-24 volts D.C. and 0-6 amps. output.	Check local electronics outlet
6. Esterline Angus Model A602X Operations 10-pen event recarder. Portable case with No. 2 hand-wound spring chart drive. Cammon return with 6 or 12 volt D.C. pen elements (specify one).	Local Esterline Angus Distributar
7. One pint red ink. Prt. No. 61101-R	Do.
8. 24 Esterline charts No. 1710-C, 3 inches per hour.	Do.
9. Cable. 6 copper strands minimum, shielded. Strand size No. 14-19 AWG.	Local Electrical Supplier ar NI cond. surplus.
10. Ohm meter (for troubleshooting wind systems). Triplett Valt-ohm-milliammeter Model 310. L. B. Walker Radio Co. Cat. No. 3018	L. B. Walker Radio Co. 300 Bryant St. Denver, Colorado 80202

NOTE: Spare anemometers and vanes are essential.

II. PRECIPITATION

Item	Source
1. Recording rain and snow gage Belfort Cat. No. 5-780 with 12-inch dual traverse. LESS CHART DRIVE AND CYLINDER BUT WITH (100) 192 hour charts No. 5-4046B, complete with pen, ink, and dash pot fluid.	Belfort Instrument Co. 4 North Central Avenue Baltimore, Maryland 21202
2. Model 301D drum chart drive, battery actuated, 3.0 volts D.C. for recording rain and snow gage—drum height 6 5/8 inches. With power pack. Gears for 192 HOUR CHART.	Kingmann-White, Inc. P. O. Box G Placentia, Calif. 92670
3. Standard 8-inch can, 42 inches in length. Galvanized, painted a flat black.	Rex Industries 625 North 335 West Salt Lake City, Utah 84100
4. Support for 8-inch can, with angle iron legs.	Do.
5. Weather Bureau weighing scale. Detecto Mod. No. 0127-H-40, 2-revolution—40-pound capacity, circular dial with decal (reads directly in inches water for 8-inch can) without cover glass or sash. Adjustable tare pointers.	Environmental Science Services Administration. U. S. Weather Bureau, Executive Boulevard Bldg. 5, Room 627 Rockville, Maryland 20852 Atten: Mr. E. Lucas (AD 112)
6. Swiss snow kit (Schneewaage) 1 Federwaage Type Nr. 491b 0-300 g Teilung 2 zu 2 g SET TARE AT ZERO. 1 Rohr 0.5 ltr. inhalt aus Aluminum 196 mm x 57 ∅ Di	Ernst Strohmeier Kreuzstrasse 52 Rapperswil SG SWITZERLAND

[11] *Trade and company names are used for the benefit of the reader, and do not imply endorsement or preferential treatment by the U. S. Department of Agriculture.*

III. TEMPERATURE

Item	Source
1. Townsend all metal thermometer support. Weksler Cat. No. 322A.	Weksler Instrument Corp. 195 East Merrick Road Freeport, New York 11520
2. Maximum thermometer. H. J. Green Cat. No. 101. Range -38° F. to 110° F. approx. One replacement max. therm. without backing.	Henry J. Green Instrument Co. 2500 Shames Drive Wespbury, New York
3. Minimum thermometer. H. J. Green Cat. No. 108—amber colored alcohol. Range -50° F. to +110° F. approx.	Do.
4. Hygrothermograph, vertical drum type, Belfort Cat. No. 5-594, LEST CHART DRIVE AND CYLINDER BUT WITH (100) 176 hour charts No. 5-209-WB. Complete with pen and ink.	Belfort Instrument Co. 4 North Central Avenue Baltimore, Maryland 21202
5. Model 301D Drum chart drive, battery actuated, 3.0 volts D. C. for hygrothermograph. Drum height 5 1/8 inches. With power pack. Gears for 176 HOUR CHART.	Kingmann-White Inc. P. O. Box G Placentia, Calif. 92670
6. Instrument shelter, medium size. U. S. Weather Bureau Spec. No. 450.0615. Cotton region type.	Science Associates 230 Nassau Street Box 230 Princeton, New Jersey 08540

IV. PRESSURE (ATMOSPHERIC)

Item	Source
1. Precision microbarograph, U.S.W.B. Spec. No. 450.7221. Chart ratio 2 1/2 to 1. Chart graduation in inches corrected to sea level. Specify spot elevation of area where microbarograph will be operated. Complete with pen, ink, and one set of charts No. 5-1071X weekly. Spring driven chart drive.	Belfort Instrument Co. 4 North Central Avenue Baltimore, Maryland 21202

V. TEST FIELD INSTRUMENTS

Item	Source
1. Ram penetrometer with 4 extension sections and 1- and 2-kg ram drivers.	Walter Buser Kleinmechanishe Werkstatte, Karstlernstrasse 5 Zurich, 43, SWITZERLAND
2. Triple beam balance. Ohaus model 750-S. (Keep at base station).	Contact local scientific supply house.
3. Stainless steel tube stock for making density tubes—304 WD stainless steel tubing, 2 3/8 inch O.D., .049 inch wall. Cut tubes 19.05 cm long and bevel one edge.	Contact local tubing distributor.
4. Plastic caps for 500 cm^3 tubes.	Test Lab. Corporation 216 N. Clinton Street Chicago, Illinois 60606
5. Shear frame: 1.9 cm depth; 10.2 cm front width; 9.7 cm back width. Two bars at 1/3 and 2/3 of total length. (See fig. 11). Bottom edges beveled. Wall thickness about 0.3 mm.	Contact local sheet metal shop.
6. Chatillon Gauge-R Catalog 516-1000. Graduated in pounds and grams.	Contact local scientific supply house.
7. Dial thermometers for snow profiles. Weston Model No. 226. Range -100° C. to +40° C.	Weston Electric Instrument Corp. Newark, New Jersey
8. Snow shovel. D-handle aluminum with square blade. Model 4A Zephyr-weight.	Wood Shovel and Tool Co. Piqua, Ohio (Order through local hardware outlet).
9. Snow pit wall brush. For hard snow. Plastic whisk broom. For soft snow: 3-inch nylon paint brush.	Local hardware store.

V. TEST FIELD INSTRUMENTS

Item	Source
10. Folding metric carpenter's rule. 2 meters long.	Local drafting store.
11. Hand lens. Double pocket lens, 2X-4X-8X. K.E. No. 830360	Do.
12. Millimeter Reticle—1 mm. plastic 2 inch by 3 inch approx.	General Biological Supply House Chicago, Illinois

Gardner, Noel C., and Judson, Arthur.
1970. Artillery control of avalanches along mountain highways. USDA Forest Serv. Res. Pap. RM-61, 26 p., illus. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado 80521.

Presents planning and operational procedures, and discusses criteria for avalanche control and the evaluation of avalanche hazard based on field data. Outlines a method for determining when gunfire should commence. Gives basic information necessary far formulating operational forecasts far highway maintenance and avalanche control personnel based on: mountain weather forecasts, traffic density, and current snow conditions. Explains instrument needs in detail.

Key words: Avalanches, snow density, anemometers, meteorological instruments, roads.

Gardner, Noel C., and Judson, Arthur.
1970. Artillery control of avalanches along mountain highways. USDA Forest Serv. Res. Pap. RM-61, 26 p., illus. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado 80521.

Presents planning and operational procedures, and discusses criteria far avalanche cantral and the evaluation of avalanche hazard based on field data. Outlines a method for determining when gunfire should commence. Gives basic information necessary for formulating operational forecasts for highway maintenance and avalanche control personnel based on: mountain weather forecasts, traffic density, and current snow conditions. Explains instrument needs in detail.

Key words: Avalanches, snow density, anemometers, meteorological instruments, roads.

Gardner, Noel C., and Judson, Arthur.
1970. Artillery control of avalanches along mountain highways. USDA Forest Serv. Res. Pap. RM-61, 26 p., illus. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado 80521.

Presents planning and operotional procedures, and discusses criteria for avalanche control and the evaluation of avalanche hazard based on field data. Outlines a method for determining when gunfire should commence. Gives basic information necessary for formulating operational forecasts for highway maintenance and avalanche control personnel based on: mountain weather forecasts, traffic density, and current snow conditions. Explains instrument needs in detail.

Key words: Avalanches, snow density, anemometers, meteorological instruments, roads.

Gardner, Noel C., and Judson, Arthur.
1970. Artillery control of avalanches along mountain highways. USDA Forest Serv. Res. Pap. RM-61, 26 p., illus. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado 80521.

Presents planning and operational procedures, and discusses criteria for avalanche control and the evaluation of avalanche hazard based on field data. Outlines a method for determining when gunfire should commence. Gives basic information necessary for formulating operational forecasts for highway maintenance and avalanche control personnel based on: mountain weather forecasts, traffic density, and current snow conditions. Explains instrument needs in detail.

Key words: Avalanches, snow density, anemometers, meteorological instruments, roads.

About The Forest Service. . . .

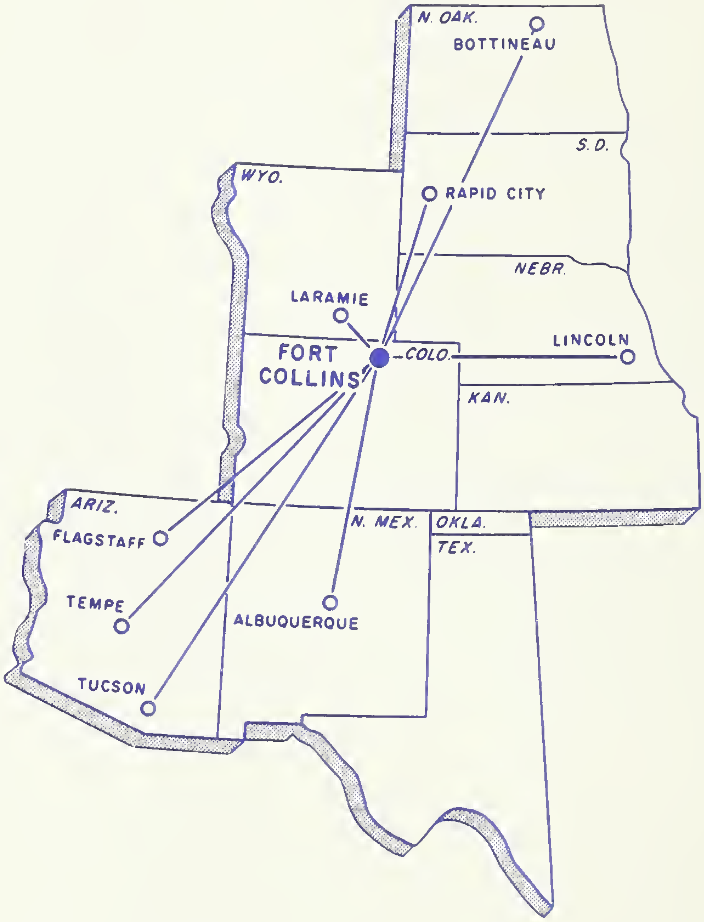
As our Nation grows, people expect and need more from their forests—more wood; more water, fish and wildlife; more recreation and natural beauty; more special forest products and forage. The Forest Service of the U. S. Department of Agriculture helps to fulfill these expectations and needs through three major activities:

- *Conducting forest and range research at over 75 locations ranging from Puerto Rico to Alaska to Hawaii.*
- *Participating with all State forestry agencies in cooperative programs to protect, improve, and wisely use our Country's 395 million acres of State, local, and private forest lands.*
- *Managing and protecting the 187-million acre National Forest System.*

The Forest Service does this by encouraging use of the new knowledge that research scientists develop; by setting an example in managing, under sustained yield, the National Forests and Grasslands for multiple use purposes; and by cooperating with all States and with private citizens in their efforts to achieve better management, protection, and use of forest resources.

Traditionally, Forest Service people have been active members of the communities and towns in which they live and work. They strive to secure for all, continuous benefits from the Country's forest resources.

For more than 60 years, the Forest Service has been serving the Nation as a leading natural resource conservation agency.


N. DAK.
BOTTINEAU
S. D.
WYO.
RAPID CITY
NEBR.
LARAMIE
LINCOLN
FORT COLLINS
COLO.
KAN.
ARIZ.
N. MEX.
OKLA.
TEX.
FLAGSTAFF
TEMPE
ALBUQUERQUE
TUCSON